RUTGERS
Center for Advanced Infrastructure and Transportation

QUARTERLY PROGRESS REPORT

Project Title:	The Effect of WMA on RAP in Hot Mix Asphalt (2010-04)
RFP NUMBER: 200X-XXX	NJDOT RESEARCH PROJECT MANAGER: Nahzat Aboobaker
TASK ORDER NUMBER: TO 254 / RU Acct 4-32449	PRINCIPAL INVESTIGATOR: Thomas Bennert, Ph.D.
Project Starting Date: 05/01/2010 **Original** Project Ending Date: 04/30/2012 **Modified Completion Date:**	Period Covered: 3rd Quarter 2011

Task #	Task	% of Total	Fixed Budget	% of Task this quarter	Cost this quarter	% of Task to date	Total cost to date
1	Literature Search	2.10%	$ 3,500	0.00%	$ -	100.00%	$ 3,500
2	WMA RAP Coating	42.40%	$ 137,281	35.00%	$ 48,048	90.00%	$ 123,552
3	WMA Mixture Design	23.70%	$ 79,047	25.00%	$ 19,762	75.00%	$ 59,284
4	Pilots & Acceptance	25.70%	$ 85,203	5.00%	$ 4,260	15.00%	$ 12,780
5	Final Report	6.10%	$ 25,000	0.00%	$ -	0.00%	$ -
6		0.00%	$ -	0.00%	$ -	0.00%	$ -
7		0.00%	$ -	0.00%	$ -	0.00%	$ -
8		0.00%	$ -	0.00%	$ -	0.00%	$ -
9		0.00%	$ -	0.00%	$ -	0.00%	$ -
10		0.00%	$ -	0.00%	$ -	0.00%	$ -
11		0.00%	$ -	0.00%	$ -	0.00%	$ -
12		0.00%	$ -	0.00%	$ -	0.00%	$ -
13		0.00%	$ -	0.00%	$ -	0.00%	$ -
14		0.00%	$ -	0.00%	$ -	0.00%	$ -
15		0.00%	$ -	0.00%	$ -	0.00%	$ -
16		0.00%	$ -	0.00%	$ -	0.00%	$ -
17		0.00%	$ -	0.00%	$ -	0.00%	$ -
18		0.00%	$ -	0.00%	$ -	0.00%	$ -
19		0.00%	$ -	0.00%	$ -	0.00%	$ -
20		0.00%	$ -	0.00%	$ -	0.00%	$ -
	TOTAL	100.00%	$ 330,031		$ 72,070		$ 199,116

Blue text is entered once at the beginning of the project
Green text is updated ever quarter
Black text is automatically updated or static

Project Objectives:

The objective of NJDOT 2010-04, *The Effect of Warm Mix Asphalt on RAP in HMA*, is to determine whether recycled asphalt pavement (RAP) can be used at typical and higher percentages in warm mix asphalt (WMA). As stated in the RFP, due to the fact this will be highly dependent on how the final mixture is produced, much of the work is required to be conducted on the WMA mixtures. Key issues that will be addressed during the research project are; 1) Appropriate RAP percentages due to potential of decreased RAP and virgin asphalt binder blending; 2) Possible mixture design modifications for WMA technologies and additives, including foamed asphalt; 3) Possible recommendations for

minimum production temperature and storage times of warm mix asphalt and 4) Acceptance procedures for allowing the use of current and new WMA technologies and additives.

Project Abstract:

Warm mix asphalt refers to asphalt concrete mixtures that are produced at temperatures approximately 40 to 70 °F cooler than typically used in the production of hot mix asphalt. The goal with warm mix asphalt is to produce mixtures with similar strength, durability, and performance characteristics as hot mix asphalt using substantially reduced production temperatures. There are important environmental and health benefits associated with reduced production temperatures including: lower greenhouse gas emissions, lower fuel consumption, and reduced exposure of workers to asphalt fumes. Lower production temperatures can also potentially improve pavement performance by reducing binder aging, providing added time for mixture compaction, and allowing improved compaction during cold weather paving.

Warm mix asphalt technologies were first introduced in Europe in the late 1990's as one measure to reduce greenhouse gas emissions. The National Asphalt Pavement Association has been instrumental in bringing these technologies into the United States with several demonstration projects being constructed since 2004. These projects have demonstrated the feasibility of using warm mix processes in the United States. Pavements have been successfully constructed using various warm mix processes with only minimal changes to equipment and quality control practices. These projects have served the important function of introducing warm mix asphalt to agency and contractor personnel, demonstrating the constructability of warm mix asphalt and providing data on energy usage and emissions. They also provide critically needed pavement sections for monitoring the performance of warm mix asphalt. Recently, a Warm Mix Asphalt Technical Working Group (TWG) has been assembled by the Federal Highway Administration (FHWA) to help guide future efforts to implement this technology. Dr. Thomas Bennert, the Principle Investigator (PI) for this proposal, has recently been elected to this organization.

One of the critical issues facing warm mix asphalt is the lack of a formal mixture design procedure. To date, properly designed hot mix asphalt concrete has served as the design for the warm mix projects constructed in the United Sates. However, the potential inclusion of higher RAP contents and plant systems that utilize foaming techniques may require modifications to the current Superpave procedure used for hot mix asphalt. If warm mix asphalt is to replace or used in conjunction with hot mix asphalt in the future, a laboratory mixture design procedure for warm mix asphalt must be established. Current efforts are underway under NCHRP 9-43 (Bonaquist, 2007) that have recommended modifications to Superpave, but to date, nothing has yet to be adopted.

Another critical issue which needs further evaluation is the use of RAP, and higher RAP percentages, in conjunction with WMA. Recent work by Bennert (2009) and Mehta (2009) has indicated that during hot mix asphalt production, it is highly unlikely that full blending between the RAP and virgin asphalt binders exist. Bennert and Dongre (2009) showed this through the backcalculation of the effective asphalt binder properties of RAP mixtures by dynamic modulus testing and analytical techniques, while Mehta (2009) showed this through coating studies. When blending does not occur, an under-asphalted condition occurs due to a decrease in film thickness on the virgin aggregates. This

was validated in mixture fatigue testing (Flexural Beam Fatigue and Overlay Tester) conducted by Bennert (2009). Therefore, if blending does not occur at elevated temperatures, it is highly unlikely that blending of RAP and virgin binders occur at lower temperatures. However, what may help in counter-acting the lack of binder blending is the reduced oxidative aging of the asphalt binder and reduced levels of asphalt binder absorption at lower production temperatures. Unfortunately, even though this may provide a more fatigue resist mix, rutting susceptibility may become an issue. The development and adoption of a WMA technology/additive Acceptance Procedure that is based on mixture performance testing would certainly help NJDOT gain confidence in the future adoption of warm mix asphalt.

1. Progress this quarter by task:

Task 1 – Literature Search (100% Completed)

The literature review is completed and will be submitted at the Quarterly Meeting. The Literature Review will include the proposed protocols developed during the NCHRP 9-43 Project, *Mix Design Practices for Warm Mix Asphalt*. Based on recommendations from NCHRP 9-43, Warm Mix Asphalt (WMA) can be designed with only minor changes to AASHTO R35, *Superpave Volumetric Design for Hot Mix Asphalt (HMA)*. Major differences are going to be in the specimen fabrication procedures and including a testing procedure to verify coating and compactability of the WMA mixtures due to the reduced mixing and compaction temperatures.

One major obstacle for the laboratory design process is going to occur for plant foaming processes. Due to the manner in which the foamed asphalt is made, a laboratory would be required to purchase a "foamer" to actually conduct the mixture design. At the moment, there are only two devices on the market, both in excess of $35,000.

Some of the major conclusions developed during the NCHRP 9-43 study were:

1. For asphalt mixtures using the same aggregates and binders and having an asphalt binder absorption less than 1 percent;
    a. Volumetric properties of WMA and HMA are very similar
    b. However, compactability, moisture sensitivity, and rutting resistance may be different when design at WMA mixing and compaction temperatures. Therefore, laboratory performance tests are required to ensure performance.
2. Currently, asphalt binder grade is recommended to be conducted in the same manner as in AASHTO R35. Field validation testing did not support high temperature grade bumping, even though rutting resistance and moisture damage potential slightly of the asphalt mixtures slightly increased in the WMA mixtures. Again, another reason for the need to incorporate mixture performance testing.
3. When incorporating RAP in WMA for mixture design and/or plant production, the high temperature grade of the RAP needs to be determined and MUST be lower than the compaction temperature of the WMA mixture. In most cases for New Jersey, if the high temperature PG grade of the RAP was approximately 100 to 94^{o}C, this would limit compaction temperatures to 200^{o}F.

4. Coating of the asphalt mixtures during design should be conducted using AASHTO T195, *Determining Degree of Particle Coating of Asphalt Mixtures*
5. Compactability of the asphalt mixtures is recommended via the following;
    a. Use 4 gyratory samples
    b. Determine maximum specific gravity (Gmm) of the mixture
    c. Short term oven age the mixtures at compaction temperature for 2 hours
    d. Determine the number of gyration to achieve 92% of Gmm at compaction temperature and 30^{o}C below compaction temperature
    e. Ratio of gyration at 30oC below compaction temperature to gyration at compaction temperature should be less than 1.25
6. For Rutting Resistance, use the Flow Number test in accordance to AASHTO TP79, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT).* Test and Pass/Fail criteria in accordance to NCHRP Project 9-33 conditions.

The Literature Review also discusses the debate as to whether or not blending between RAP binder and virgin binders occurs, even at hot mix temperatures. Some members of Federal Highway have even mentioned that they believe that very limited amounts of blending actually occurs – the Literature Reviews discusses both sides of the argument and testing/analysis procedures to evaluate this.

Task 2 – WMA RAP Coating Experiment (90% Completed)

OBJECTIVE

The objectives of this study are:

1. Determine the degree of blending occurring in the WMA consisting of 25% RAP by total weight of the mix and changes in the following parameters:
    a. Mixing temperature,
    b. Mixing time,
    c. Conditioning time,
    d. WMA technologies, and
2. Conduct Gel Permeation Chromatography (GPC) test to determine molecular weight as a measure of polymer degradation due to short term aging, both at WMA temperatures (133ºC) and HMA (163ºC).

Literature Review

Degree of Blending

Previous studies have shown strong evidence that neither black rock theory nor full blending occur but partial blending *(6,7,8)*. A study conducted by Huang (2005) in which virgin aggregates above the No.4 sieve were mixed with fine RAP aggregates below the No.4 sieve with no virgin binder aided in observing and quantifying the amount RAP binder interaction. This study was conducted with varying

proportions of RAP (10%-30%) and mixed at 190°C for 3 minutes. Results from the Huang (2005) study concluded that approximately 11% of RAP binder was actually mobilized which would indicate a degree of blending far less than the 100% assumption at most agencies *(6).*

In another study conducted by Shirodkar (2009), gap-graded RAP aggregates (No aggregates between the No.4 and No. 8 sieve) were heated to remove any preexisting moisture. Virgin coarse aggregates were washed to eliminate fines and RAP aggregate was sieved finer than the No. 8 sieve. The virgin and RAP material was then mixed at 350°F for 1, 2, and 3 minutes and at RAP contents of 10%, 25%, and 40% using a mechanical mixer. It was observed that percentage of RAP binder transfer increased after one minute and stopped increasing in the range of two to three minutes. The increase in RAP percentage also showed a decrease in RAP binder transfer mostly due to the fact that RAP aggregate is more likely to transfer binder to other RAP aggregate at higher RAP percentages *(7).*

Shirodkar (2009) developed an equation to quantify the degree of blending between virgin coarse aggregate and RAP fine aggregate using the binder properties from extracted and recovered samples. This involved mixing a gap graded asphalt mixture in which virgin aggregate comprised the coarse aggregate and RAP comprised the fine aggregate. The asphalt mixture was then manually separated into coarse and fine mixed aggregate. The separated coarse and fine aggregates were then extracted and recovered (AASHTO T-319) followed by binder property testing (AASHTO M-320). A blending ratio was developed using the RTFO G*/sin (δ) parameter from AASHTO M-320. The blending ratio equation was determined as follows in Equation 1:

$$Blending\ Ratio = \frac{G^*/sin(\delta)_{blend\ binder\ virgin\ agg} - G^*/sin(\delta)_{blend\ binder\ RAP\ agg}}{G^*/sin(\delta)_{virgin\ binder} - G^*/\sin(\delta)_{RAP\ virgin\ binder\ 0\ blend}} \quad (1)$$

The numerator in Equation 1 presents the difference between the RTFO G*/sin (δ) parameter of the virgin and RAP material. The denominator represents the condition in which zero blending or no mobilization of RAP binder occurs. Since no RAP is activated, the binder extracted from virgin aggregate is expected to have the same properties as virgin binder material, which is represented in the first half of the denominator. Furthermore, RAP binder is not expected to mobilize during mixing but will still be removed during the extraction and recovery process. *(7)* In order to replicate the black rock effect, film thicknesses around virgin and RAP aggregates were determined using the Bailey's method. Bailey's method approximates the total surface area of aggregates within a mixture using surface area factors obtained from the overall gradation. This total surface area is then used in conjunction with the asphalt content of the mixture for determining the approximate film thickness around each aggregate *(15, 16, 17).* The film thickness was assumed to be the same for each aggregate in order to simplify calculations.

Nguyen (2009) concluded that the full blending assumed by a majority of transportation agencies does not occur by studying colored virgin binder and RAP aggregate imaging.. Fine and coarse RAP was considered in this study with a variety of mixing times ranging from 2 to 8 minutes for coarse RAP and 1 to 8 minutes for fine RAP. It was observed that coarse RAP led to an increased mixing effort and higher thermal energy requirements to prevent RAP from collecting. Although increased mixing time and fine RAP increased the homogeneity observed through slicing of compacted specimens, RAP collection was still evident in various combinations of conditioning and mixing time *(8).*

Polymer Degradation

Polymer degradation is the breakdown and deterioration of performance in modified binders due to oxidation and heat. Lu and Isaccson (1998, 2000) concluded that the rheological properties of

asphalt binder were adversely affected by oxidation and styrene-butadiene-styrene (SBS) degradation in SBS modified binders. Gel permeation chromatography (GPC) was used to measure the molecular weights of the binder and polymer components of the binder *(9, 10).* GPC measures the molecular weight of the largest particles first which are the polymers and a reduced molecular weight typical means the reduction of the polymer. Results showed that as heat and oxidation increased, polymer molecular weight decreased indicating polymer degradation as a result of stabilization with chemical constituents within the binder. Unlike the polymer, the binder increased in molecular weight as a result of the increase of the high molecular weight binder constituent known as asphaltenes. *(11)*

EXPERIMENTAL PROCEDURE

Materials and Scope

In this study, the base binder consisting of a SBS-modified PG76-22 was modified with two WMA additives, totaling two binders for the degree of blending study. One RAP source was used for the RAP binder and RAP aggregate portion of the study. A controlled gradation containing two aggregates and RAP was used.

WMAT 1 and WMAT 2 were the two WMA additives selected for this study. Currently WMAT 1 and WMAT 2 are some of the most widely used WMA additives in the paving industry and thus the reason for their selection in this study. A brief overview of these additives and how they operate will be provided.

WMAT 1 is categorized as a synthetic emulsifier in that it chemically reacts to blend two previously immiscible products which are the asphalt and aggregate. Typical hot mix asphalt uses higher temperatures to reduce viscosity and promote coating. WMAT 1 reduces the heat energy required and uses chemical energy to promote coating. WMAT 1 is comprised of surface active agents (surfactants), which have polar and non-polar properties. These surfactants are able to react with the non-polar asphalt and polar aggregate bringing the two together at a lower temperature. *(12)*

WMAT 2 is categorized as a viscosity reducer of both mixing and compaction temperature. WMAT 2 is long chain aliphatic polymethylene hydrocarbon crystalline that originates from byproducts of the Fischer-Tropsch process on natural gases or coal. The byproducts of interest are the Fischer-Tropsch waxes which have long hydrocarbon chains which lead to higher melting points. WMAT 2 is completely soluble in asphalt binder at temperatures higher than 248°F (120°C) and will not separate in storage. The crystalline properties at lower temperatures of asphalt provide rut resistance and can be considered an alternative to SBS modification *(13).*

Material Preparation

In order to measure the amount of RAP binder transfer between fine and coarse aggregate during the mixing and conditioning process preliminary preparations of RAP and aggregate were necessary. Coarse aggregate that is greater than the No. 4 (4.75 mm) sieve will act as the virgin aggregate material while the RAP sieved smaller than the No. 8(2.38 mm) contributes the finer portions of the gradation in addition to RAP binder. This in turn leaves a gap between the No. 4 (4.75 mm) sieve and the No. 8 (2.38 mm) creating a gap gradation which will allow for easier separation of course and fine material. The following aggregate and RAP preparation was performed: sieve the virgin aggregate above the No. 4 (4.75 mm) sieve, wash the aggregate to remove any fines that would pass the No. 4(4.75 mm), dry the aggregate in the oven, and sieve the RAP to be less than No. 8 sieve (2.38 mm).

Gradation and Binder Content

A job mix formula (JMF) was provided by a mixing plant and was modified to accommodate the material preparation mentioned in the previous section. Figure 1 shows the JMF provided, and the modified JMF used, for the degree of blending study. The intent was to replicate the JMF as much as possible while maintaining a gap gradation.

Once the RAP was sieved to be less than the No. 8 sieve (2.38 mm), binder content was determined in order to calculate amount of RAP binder present. Ignition oven method (AASHTO T-308) was the test procedure used to obtain the fine RAP binder content which was 8.27%. This binder content helped to determine the proportion of RAP binder that is effective in the overall binder content of the mixtures.

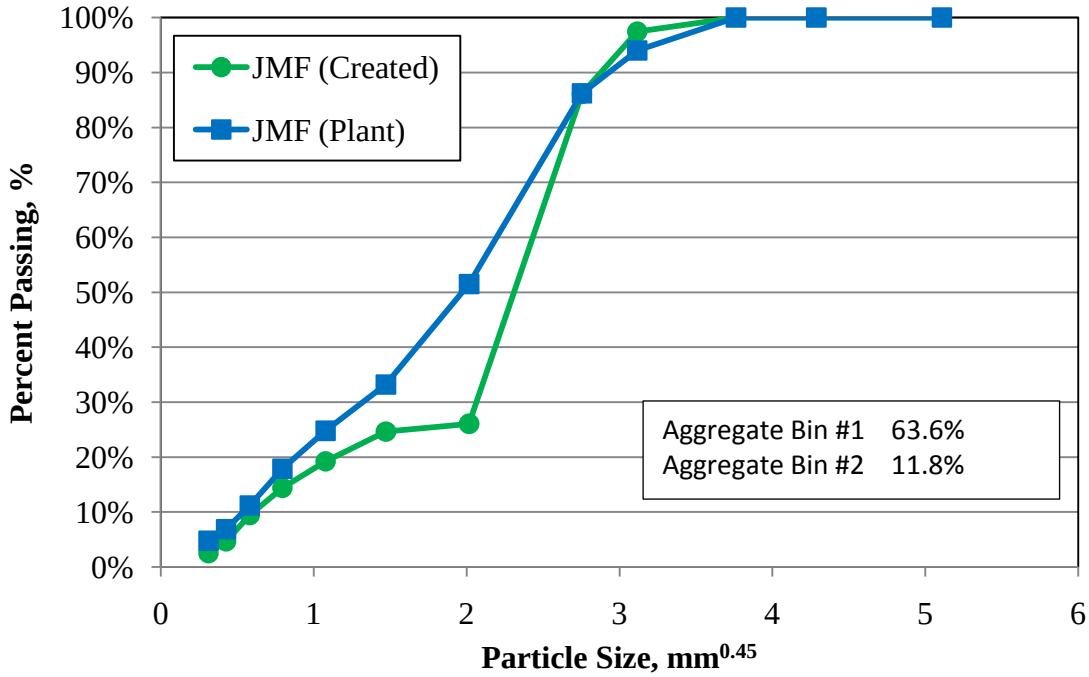

Figure 1 Gradation of the JMF and the Gap Gradation for 25% RAP

Testing Matrices

In order to encompass various combinations of plant conditions as well different WMA technologies, a series of specimens were mixed and prepared. The testing matrix is presented in Table 1. Two WMA binders were used, two different conditioning times, two different mixing times, and two different mixing temperatures totaling 24 combinations of possible plant mixing conditions. An extraction and recovery procedure is required for the manually separated coarse and fine aggregate.

Table 1 Testing Matrix for Degree of Blending

		Number of Extraction & Recoveries			
24 Total Combinations	**WMA Type**	**WMAT 1**		**WMAT 2**	
Mixing Temperature	**Conditioning Time / Mixing Time**	**2 Hours**	**3 Hours**	**2 Hours**	**3 Hours**
260°F (126.7°C)	**1 Minute**	2	2	2	2
	5 Minute	2	2	2	2
315°F (157.2°C)	**1 Minute**	2	2	2	2
	5 Minute	2	2	2	2

The polymer degradation testing regimen is presented in Table 2, in which number of replicates is shown. A uniform set of the three binders were created using the rolling thin film oven (RTFO) procedure AASHTO T-240 *(21).* The three binders were tested at three of the following aging conditions: Original binder with no aging; RTFO aging at 133°C to simulate short term aging at warm mix plant conditions; and RTFO aging at 163°C to simulate short term aging at hot mix plant conditions. The time in the RTFO was controlled at 1 hour and 25 minutes in accordance to specification. The number average molecular weight (M_n) and molecular weight (M_w) were measured from the gel permeation chromatography test and replicated.

Table 2 Testing Matrix for Polymer Degradation

WMAT 1	Polymer Peak		Binder Peak	
	M_n	M_w	M_n	M_w
Original	2	2	2	2
RTFO at 133°C	2	2	2	2
RTFO at 163°C	2	2	2	2
WMAT 2	**Polymer Peak**		**Binder Peak**	
	M_n	M_w	M_n	M_w
Original	2	2	2	2
RTFO at 133°C	2	2	2	2
RTFO at 163°C	2	2	2	2
PG 76-22 (Control)	**Polymer Peak**		**Binder Peak**	
	M_n	M_w	M_n	M_w
Original	2	2	2	2
RTFO at 133°C	2	2	2	2
RTFO at 163°C	2	2	2	2

Binder Properties

After mixing and conditioning, the virgin and RAP aggregates were separated by heating aggregates at 110°C for 10 minutes then manually separated. The binder from the separated aggregates was extracted and recovered using AASHTO T164 and ASTM, respectively. *(20, 22)* The rolling thin film oven (RTFO) G*/sin (δ) property of the extracted and recovered binder was determined at 76°C via AASHTO T-315. The temperature of 76°C was selected as the high PG-grade for the 25% RAP mix with PG 76-22 virgin binder. The G*/sin (δ) of RTFO binder was selected for two reasons: the amount of binder required for a RTFO sample can be obtained with one single extraction and recover procedure and the binder properties at high temperatures are generally more sensitive to blending than low temperature test results *(14).*

Gel Permeation Chromatography

Gel Permeation Chromatography (GPC) is used to determine the molecular weight distribution of all of the components of asphalt binders. The sample runs through a column capable of handling a wide range of molecular weights so that all asphalt components can be captured. Since samples must be in the liquid phase for testing, asphalt is diluted in tetrahydrofuran (THF) before running through the test column.

The membrane has a certain pore size which only certain sized molecules can pass through. Therefore, the larger molecules that cannot pass through must go around the membrane. These move at a faster rate than the smaller molecules, and thus pass through first. The smaller molecules must pass through the membrane pores and take longer to get through.

To analyze the data, a diode array detector (DAD) is set to read at a wavelength of 254 nm. GPC gives peak readings for each molecular weight found within a sample. Using a computer program these peaks are integrated and analyzed to obtain the average and peak molecular weights. An example of the auto-integrated chromatograph is provided in Figure 2. The parameters of interest are M_w and M_n, which are the mean of molecular weights within the selected region. An example of this method is presented in Figure 3. The peaks of interest for this study were the polymer and binder peaks which are typically the first and second peaks of the chromatograph.

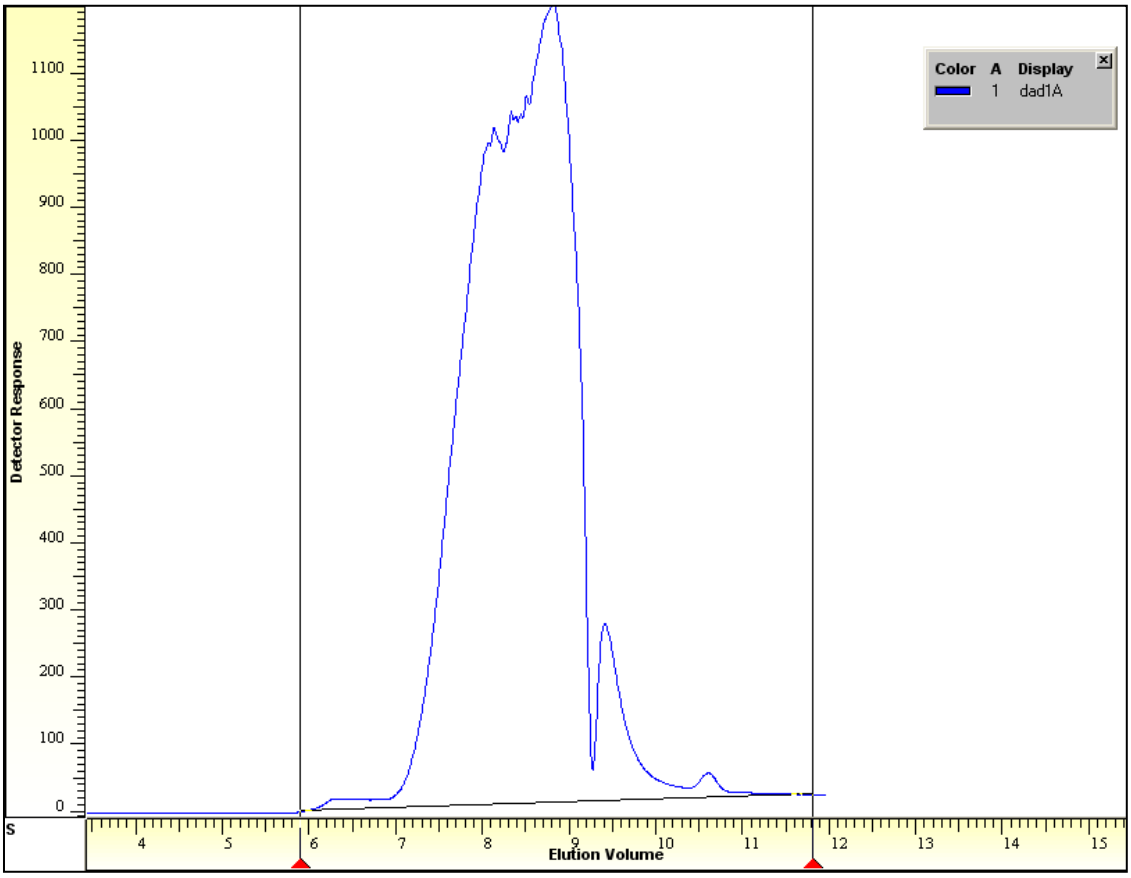

Figure 2 Example of typical asphalt chromatograph

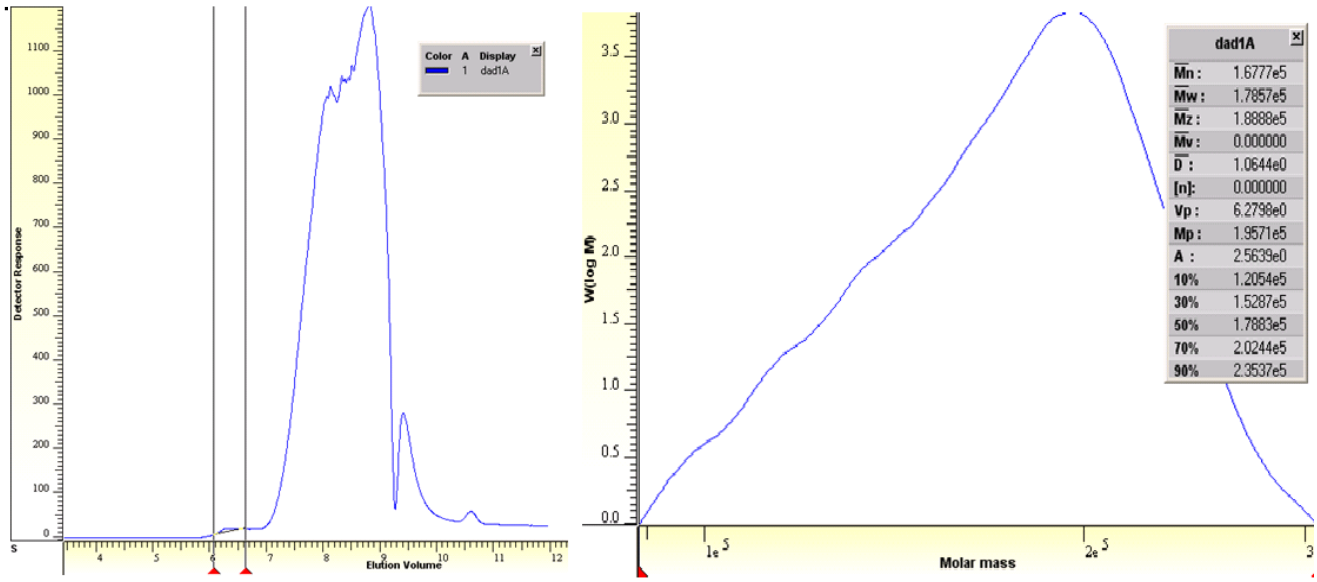

Figure 3 a) Chromatograph with the selection of the polymer peak. b) Zoomed in chromatograph with a table providing M_n and M_w of the selected portion of the chromatograph.

Procedure

The methodology of the blending study to determine the degree of partial blending is summarized as follows:

1. Determine the binder content of the RAP and the gradation of the extracted aggregates.

2. Determine the Superpave PG properties (from AASHTO T315) of the RAP binder and the virgin binder. *(19)*

3. Create a Superpave gradation for a given percentage of RAP (i.e. 25% and 35%), such that all the fine aggregates (minus #8 to 2.36 mm) are RAP and all coarse aggregates (greater than # 4 to 4.75 mm) are virgin aggregates. The Superpave gradation created in the lab will be similar to the JMF gradation for a given percentage of RAP. This gap gradation was created in order for the manual separation of virgin and RAP aggregates to be possible.

4. Consider design binder content from the JMF for the study. If the design binder content is not known, determine the design binder content (DBC) based on the Superpave mixture design.

5. Assume an initial degree of blending in the range of 0% to 100%.

6. Create the mixture at the virgin binder content (VBC) determined from Equation 2 below:

$$Binder\ Content_{(virgin)} = JMF\ Binder\ Content_{(Design)} - RAP_{(Estimated\ Working\ Binder)} \quad (2)$$

7. Separate the coated virgin and RAP aggregates after mixing by slight heating at 110°C and manually separating into above #4 and below #8 sieves.

8. Extract and recover the binder separately from the coarse virgin aggregates (plus #4) and fine RAP aggregates (minus #8).

9. Determine the Superpave PG properties (from AASHTO T315) of the blended binder on the RAP and the virgin aggregates. *(19)*

10. Determine the proportion of the virgin binder that would coat the RAP and the virgin aggregates under zero blending condition by estimating the surface area of the aggregates at each sieve size using Bailey's method.

11. Blend the RAP binder with the proportion of the virgin binder determined from step 10 above. Determine the Superpave PG properties (from AASHTO T315), such as G* / sin (δ) *(19.)*

12. Calculate the degree of partial blending from Equation 3:

$$Degree\ of\ Partial\ Blending\ (\%) = 100|1 - Blending\ Ratio| \quad (3)$$

Where:

(G*/sin(δ))blend binder virgin aggregate	-	RTFO G*/sin (δ) of blended binder coating the virgin aggregates (determined from step 8)
(G*/sin(δ))blend binder RAP aggregate	-	RTFO G*/sin (δ) of blended binder coating the RAP (determined from step 8)
(G*/sin(δ)) virgin binder	-	RTFO G*/sin (δ) of the virgin binder (determined from step 2)
(G*/sin(δ))RAP virgin binder 0 blend	-	RTFO G*/sin (δ) of the RAP and virgin binder that is coating the RAP aggregate assuming 0% blending (determined from step 10)

13. Iteration - If the degree of partial blending (determined from Step 11) is similar (within ±10%) to the calculated value in Step 5, then the degree of partial blending has been determined. It was concluded that 10% was the attainable range considering higher margins for error. However, if considerable difference exists between the two, the process will be repeated with the revised value of the RAP working binder that is obtained from Step 11 and the steps will be repeated from Step 5 onwards.

RESULTS

Degree of Blending

The assumed degrees of blending (DOB) from Step 5 in the procedure are presented in Table 3. The calculated DOB's from Step 12 are also presented alongside the assumed DOB in Table 3. The DOB's that were within a 10% range are highlighted and do not require further iteration.

Although further iteration is necessary, DOB's of different warm mix additives are similar when comparing their respective temperature, mixing time, and conditioning time combinations. No trend was observed when comparing 2 and 3 hour conditioning time. No trend is observed when comparing WMA and HMA mixing temperatures either. The 1 and 5 minute mixing times exhibited an increase in DOB in most of the combinations.

Table 3 Degree of Blending Results Matrix

WMAT 1		**2 Hours**		**3 Hours**	
260°F (126.7°C)	**1 Minute**	70	88	70	80
	5 Minute	70	95	70	84
315°F (157.2°C)	**1 Minute**	70	72	70	85
	5 Minute	80	77	80	76
WMAT 2		**2 Hours**		**3 Hours**	
260°F (126.7°C)	**1 Minute**	70	89	70	80
	5 Minute	70	91	70	83
315°F (157.2°C)	**1 Minute**	70	80	70	89
	5 Minute	70	82	70	87

Highlighted cell were within 10% of the initial assumed values

Gel Permeation Chromatography Results

Polymer Peak

The average polymer peak molecular weights are provided in Figure 4. The WMAT 2 modified binder experienced a 2% decrease in molecular weight at 133°C RTFO, a 12% decrease in molecular weight at 163°C RTFO, and an overall decrease of 13% from original to RTFO at 163°C.

The WMAT 1 polymer showed more sensitivity to aging process. The WMAT 1 modified binder experienced a 7% drop in molecular weight at 133°C RTFO, a 30% drop in molecular weight at 163°C RTFO, and an overall reduction of 35% from original to RTFO at 163°C.

The control showed an anomaly with increasing polymer peak molecular weight with 133°C RTFO aging. Polymer peak increased in this case by 22%. Although the 163°C RTFO produced an overall polymer peak drop of about 2%, maintaining the general trend.

In WMA binders, polymer peak molecular weights steadily fell from virgin condition, to RTFO condition at 133ºC, and then to RTFO at 163ºC. However, the average polymer peak molecular weights of control binder increased from virgin condition to RTFO at 133ºC, and then decreased at RTFO condition at 163ºC, before returning to its original molecular weight.

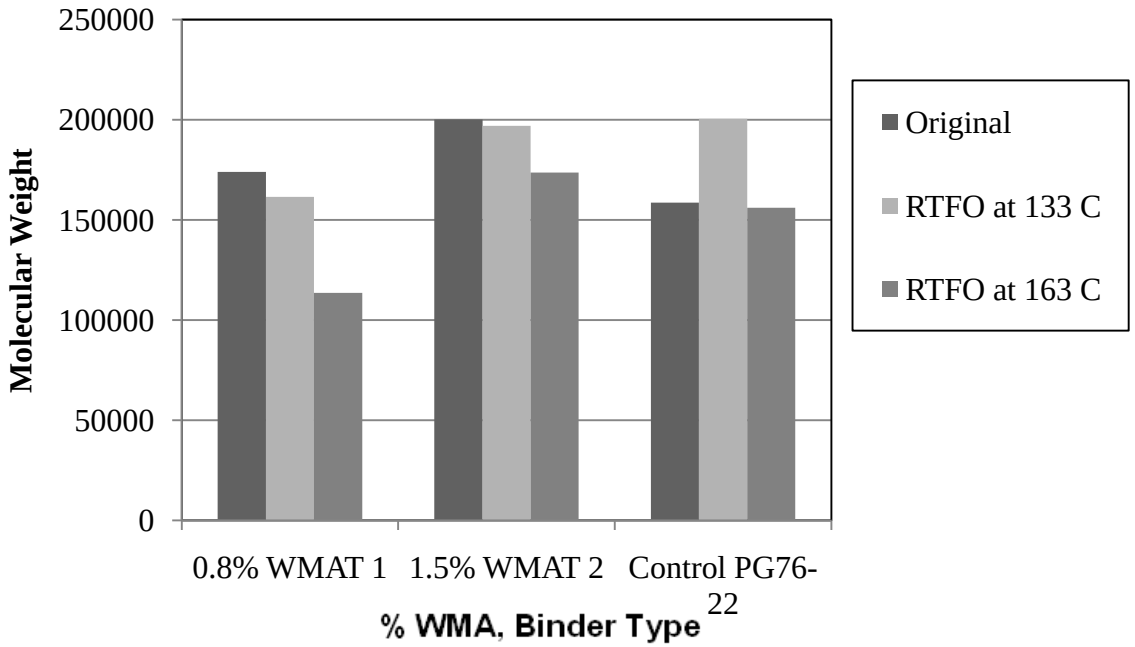

Figure 4 Polymer Peak Molecular Weight at original, RTFO 133°C and RTFO 163°C

Binder Peak

The average binder molecular peaks are presented in Figure 5. The binder peaks from the same molecular weight curves exhibited a general increase in molecular weight. WMAT 1 had greatest sensitivity while WMAT 2 exhibited the amount of sensitivity. The WMAT 2 modified binder experienced a 2% increase in molecular weight at 133°C RTFO and no increase in molecular weight at 163°C RTFO, and an overall increase of 2%.

The WMAT 1 binder exhibited more sensitivity to the short term aging process compared to the WMAT 2 and control binder. The WMAT 1 modified binder experienced a 16% decline in molecular weight at 133°C RTFO, a 47% increase in molecular weight at 163°C RTFO, and an overall increase of 38% from original to RTFO at 163°C.

The control binder showed steady increases and had marginal sensitivity. The control binder experienced a 6% increase in molecular weight at 133°C RTFO, a 12% increase in molecular weight at 163°C RTFO, and an overall increase of 18%.

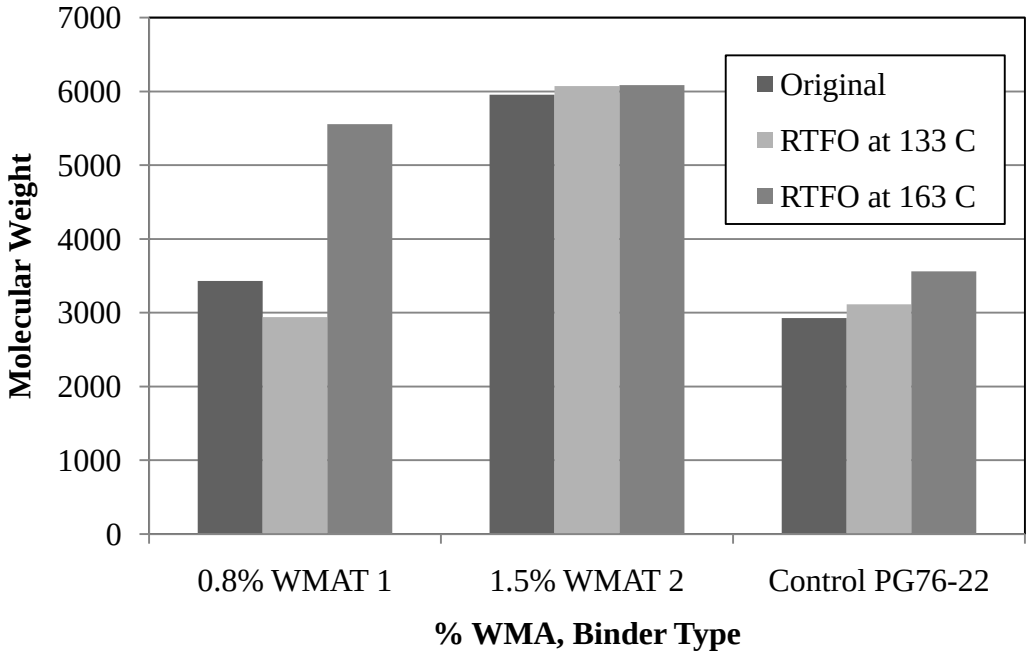

Figure 5 Binder Peak Molecular Weight at original, RTFO 133°C and RTFO 163°C

DISCUSSION

Most of the assumed DOB's from Step 5, with the exception of one combination, were 70% and resulted in further iterations being required at higher assumed DOB's for Step 5. Degree of blending does not appear to be sensitive to warm mix additive, conditioning time, and mixing temperature. DOB showed significant sensitivity to mixing time, with general increases in DOB with increased mixing. A mixing time shorter than five minutes would likely produce a similar if not higher DOB since five minutes exceeds most recommended plant mixing times. At exceeded mixing times it is possible that RAP particles began to transfer binder to themselves and not to the virgin aggregate. Shirodkar (2009) showed in a coating study between RAP and heated aggregates that RAP binder transfer levels out and begins to slightly decrease after two to three minutes *(7)*. All of the DOB results fell in the range of 70 to100%, indicating of that this range would be applicable for field conditions.

In terms of polymer degradation, the WMAT 1 modified binder showed the most sensitivity. This can likely be attributed to an unknown interaction that may be occurring between the polymer modification of the binder and the WMAT 1 product. The same may be applied to WMAT 2 although the sensitivity is not as evident as in WMAT 1. The control binder showed the least amount of overall sensitivity which could indicate that it may not be experiencing chemical reactions or viscosity reducing properties that the WMA additives introduce.

The binder peak showed a general increase in molecular weight which is a result of the aging process which increases the asphaltene content of the binder. *(11)* It can be seen that WMA conditioning temperatures resulted in less binder aging and stiffening which is an ideal paving condition and lowers the possibility of fatigue cracking.

Conclusions

The conclusions of the study are shown below:

1. Degree of blending was not adversely affected by warm mix additive, conditioning time, and mixing temperature.

2. Degree of blending was sensitive to mixing time, and it increases when mixing time increases, but may remain constant past the typical plant mixing time.

3. WMA mixtures can be handled as HMA mixtures without adversely affecting the degree of blending.

4. Degree of blending will most likely fall in the range of 70% to 100% for most plant conditions.

5. Polymer and binder molecular weights changes were no greater at WMA conditioning temperatures as compared to HMA conditioning temperatures. However, the introduction of a warm mix additive did increase the change in M_w when compared to a control binder.

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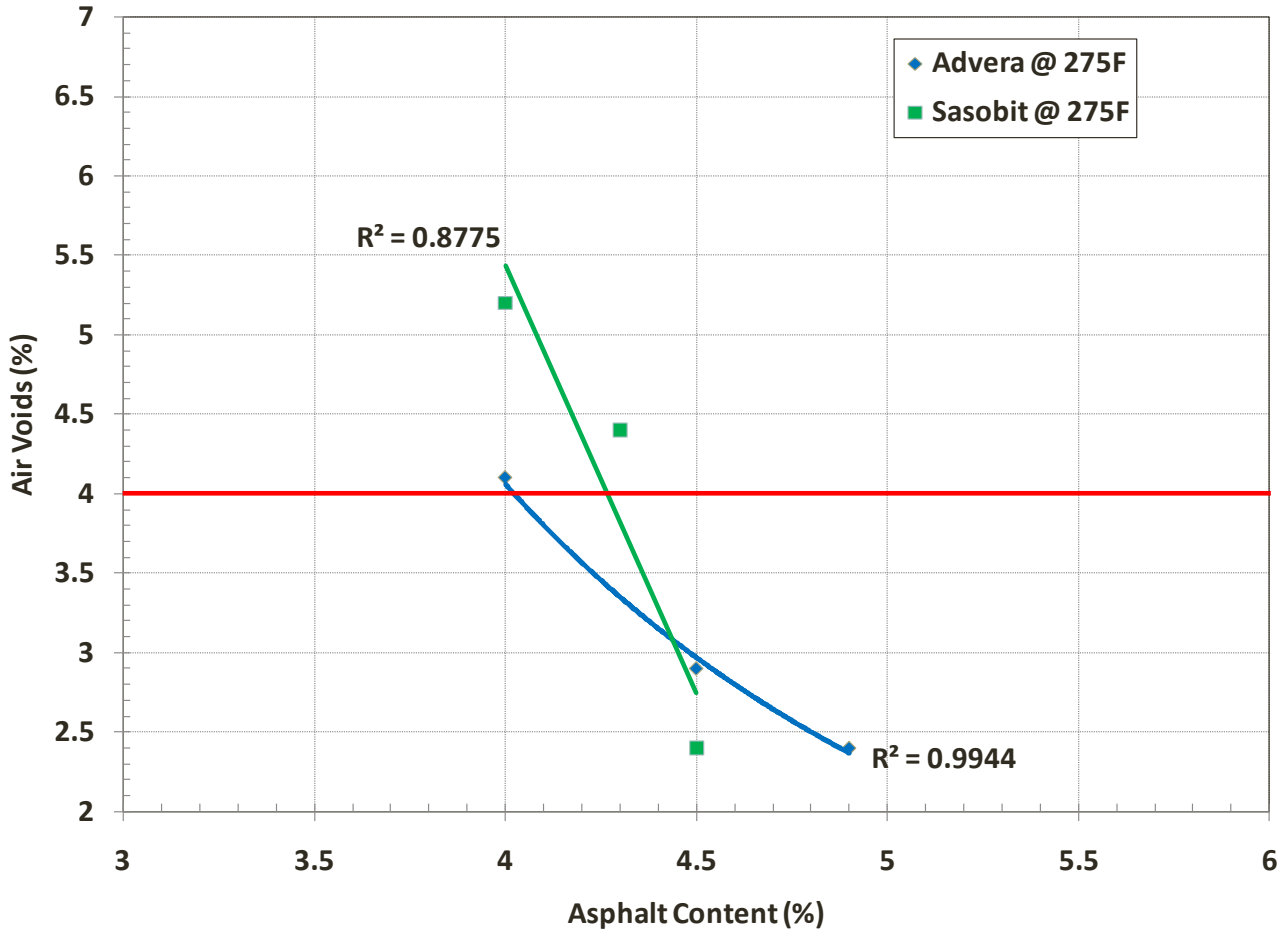
Task 3 – WMA Mixture Design Procedure Evaluation (75% Completed)

All Tensile Strength Ratio (TSR) sensitivity testing was completed and indicated the following:

- TSR's do not necessary decrease when WMA is used. Additives such as Rediset and Evotherm 3G were able to maintain, and sometimes even increase TSR when compared to HMA;
- Although TSR values increased, the wet and dry strengths of the WMA samples were found to significantly decrease. The amount of decrease in the TSR was generally proportional to the decrease in production/mixing and compaction temperature of the WMA; and
- Advera samples did not perform as well as the other WMA additives or HMA. In fact, at the 225 production temperatures, the Advera specimens did not survive the conditioning phase of the AASHTO T283.

Based on the above work, it is recommended that NJDOT consider adding a minimum wet strength criteria in addition to the already existing TSR value of 80%. At this point, there is not definitive value as to what the wet strength should be. However, discussions at the FHWA WMA Expert Task Group meetings discussed a value of 50 to 60 psi as a minimum requirement for the wet strength of dense-graded asphalt mixtures produced with WMA technologies.

Work pertaining to the WMA mixture design, as proposed by NCHRP project 9-43, is coming to an end soon. Most mixtures have the volumetric work completed and performance samples compacted and ready for testing. An example of the results is shown in the figure below. The mixture design, verified in the laboratory, had an optimum asphalt content of 4.9%. However, after the WMA additives were introduced, and mixed at a temperature of 275F, the optimum asphalt content decreased. For the Advera mix, the asphalt content decreased almost 0.9%. For the Sasobit mix, the asphalt content decreased almost 0.5%.



This ultimately could change the mixture performance properties. To evaluate this, performance samples for the WMA samples were prepared at optimum asphalt content (as shown above) and the original asphalt content of the mix design (4.9%) to determine if there is a detrimental effect due to the

new optimum asphalt content. Performance testing includes the Overlay Tester and Flow Number test.

Additional, the same type of work in being conducted on mixtures with 25% RAP, as opposed to the virgin mixes shown earlier. Mixtures with the 25% RAP were extremely dry and required an additional 0.6% of asphalt to achieve the 4% air void level. Mixture designs are being completed with the WMA additives and the data will be presented at the quarterly meeting.

Task 4 – Pilot Study and WMA Acceptance Plan (10% Completed)

The main NJDOT pilot study is planned for production in early to mid June. The project will be placed on Rt 18 from South of Route 34 to Route 9 Southbound. A NJDOT 12.5M76 is being used as the resurfacing material on the project. At the time of this report, three warm mix asphalt technologies are being used; 1) Gencor Green Machine foaming system, 2) Evotherm 3G, and 3) Either Sasobit or Advera – still depending on the contractor. Another mixture will be using the foaming system along with an anti-strip will also be produced. Each of these mixes will have 15% RAP. A higher RAP WMA has also been proposed by NJDOT, but the contractor may only decide to use approximately 20% RAP. This would leave the following mixes to evaluate during the study:

1. Control HMA
2. WMA Foaming (Gencor Green Machine)
3. WMA Foaming (Gencor Green Machine) + Anti-strip
4. WMA with Evotherm 3G
5. WMA with either Advera or Sasobit
6. WMA Foaming (Gencor Green Machine) + 25% RAP (possible)

Loose mix samples will be collected, as well as samples compacted at the asphalt plant's QC laboratory. Raw materials (aggregates, RAP and asphalt) will also be collected and utilized to produce laboratory prepared WMA samples and compare the volumetric and mechanical properties to the lab and field produced specimens. Core samples will also be taken and evaluated. A number of material properties are proposed to be evaluated after different times after construction. These include;

- Mixture stiffness
- Potential for Moisture Damage
- Rutting Potential
- Cracking Potential
- Low Temperature Cracking Susceptibility

2. Proposed activities for next quarter by task:
Final testing on baseline materials and a few replicates are needed to be completed for Task 1.

Performance testing of virgin mixes and completing the volumetric design and performance testing are proposed for Task 2.

It is hopeful that material testing will be conducted for the planned field project for Task 3.

3. List of deliverables provided in this quarter by task (product date):

4. Progress on Implementation and Training Activities:

5. Problems/Proposed Solutions:

Total Project Budget	$330,031
Modified Contract Amount:	
Total Project Expenditure to date	$199,116
% of Total Project Budget Expended	60.33%

NJDOT Research Project Manager Concurrence: _____ Date: _____